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The Detection and Identification of Underground Nuclear Explosions: A Study

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Introduction

One of the major problems encountered in the recent Geneva negotiations on the cessation of nuclear weapons tests was that of agreement on an adequate surveillance system for underground tests. Ideally, one would want a system, acceptable to both the USSR and the Western Powers, which would detect the occurrence of all underground nuclear explosions, distinguish these from earthquakes and other natural phenomena, and accurately determine their positions. Practically, one would compromise on a system which achieved these objectives with high probability for all but relatively small explosions.

There was considerable disagreement over the present feasibility of even a compromise system. Basically, the Western negotiators were less optimistic than their Eastern counterparts concerning the ability of current techniques to detect and identify a satisfactorily large fraction of even moderately large tests.

To the engineer versed in detection theory and familiar with modern data processing capabilities, the "current techniques" look, at least on cursory appraisal, most rudimentary. The natural question arises whether they might not be considerably improved by application of some of the advanced methods which had been so successful in the field of statistical communication theory. It was with this question in mind that the author undertook, during the summer of 1961, a study of the problems involved in the detection and identification of underground nuclear explosions.

The present report is an outgrowth of that study, which terminated in September 1961. It would be pleasant to state that the problem had been solved completely. Such is unfortunately not the case, but, in lieu of so satisfactory a culmination, the next best thing may be to present a digest of the study, including, in particular, one suggestion which the author feels is worth further consideration.

The report starts with a brief summary of the history of recent interest in the problem. There then follows a discussion of phenomena associated with an underground explosion that may serve as telltales of its occurrence. Of these phenomena, two are singled out for further consideration, viz., low-frequency electromagnetic disturbances and seismic disturbances.

A short section of the report is devoted to a survey of some current investigations into the not-too-hopeful possibility of the detection of low-frequency electromagnetic disturbances.

The remainder of the report is concerned with seismic detection and identification, which seem slightly more hopeful. After a brief summary of some of the pertinent facts of seismology, various possible seismic methods of detecting underground explosions and distinguishing them from earthquakes are discussed, and one is suggested as being perhaps more promising than the others.

Untutored as he was (and still is) in the fields of seismology and geology, the author tried the patience of several professionals in the field with questions that must have seemed worse than elementary to them. He is much indebted to T. Cantwell, T. Madden and S. Simpson of the M.I.T. Department of Geology, R. Phinney and S. Smith of the C.I.T. Seismological Laboratory, N. Haskel of the AFCRC Terrestrial Sciences Laboratory, and D. Linehan of the Weston Seismological Observatory for the many hours they collectively contributed to his education. His thanks are also due B. Bogert and S. Speeth of the Bell Telephone Laboratories, R. O'Rourke and M. Shuler of Edgerton, Germeshausen and Grier, Inc., and R. Ghose of Space-General Corp. for having discussed with him their work on nuclear bomb detection and identification. The author is also grateful to P. Green, R. Price and R. Wernikoff for having listened attentively and critically to his ideas at various stages of this study.

A Brief History [21]*

In the summer of 1958, the Conference of Experts to Study the Method of Detecting Violations of a Possible Agreement on the Suspension of Nuclear Tests took place in Geneva. The West was represented by the U.S., the U.K., France and Canada, and the Soviet Bloc by the U.S.S.R., Poland, Czechoslovakia and Romania. For the purposes of detection, identification and location of underground nuclear explosions, the Conference recommended a network of 180 seismic stations, spaced at intervals of 600 miles in seismic regions and 1000 miles in aseismic regions. It was concluded that this system would be capable of detecting and locating tamped** explosions within continental areas of 1 to 5 kilotons (kt) and up. Further, the system was estimated to be able to identify 90 per cent of earthquakes producing seismic effects equivalent to tamped explosions of 5 kt or more, and a few per cent of earthquakes between 1 and 5 kt equivalent. The Conference report concluded that there would be each year a thousand or more earthquakes in the 1-5 kt range and 20 (U.S.S.R. estimate) to 100 (U.S.-U.K. estimate) larger earthquakes that would not be identified as such by the system, and thus might be suspected of being explosions. It was proposed that the larger of these suspicious events be subjected to on-site inspections, the means for which were also studied.

Subsequent to the Conference of Experts report, the U.S. conducted a series of underground nuclear explosions (Hardtack II Series), in part to obtain more data on seismic detectability. The results of these tests were later studied by a panel, under L. V. Berkner, which was appointed by the Special Assistant to the President for Science and Technology. The panel concluded that the estimates made by the Conference of Experts concerning identification of earthquakes greater than 5 kt equivalent apply more accurately to explosions of greater than 20 kt equivalent; that the Conference's estimates of numbers of earthquakes per year of less than 20 kt equivalent were much too small; and that the estimates of the annual number of unidentified events above 1 kt equivalent were too small by a factor of ten.

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* Numbers in brackets refer to the Bibliography at the end of this report.

** I.e., closely coupled to the earth.

Further, it was theoretically shown in 1959* that one of the Conference's conclusions -- that the explosion of a weapon in a large underground cavity would not result in a muffling factor of more than 2 to 3 compared with the tamped case -- was in fact an incorrect conclusion. What was shown to be true is that increasing the size of the cavity beyond a critical point (at which the walls of the cavity begin to respond elastically) results in little increase in decoupling. But an increase in the size of the cavity from the tamped case (inelastic behavior of the walls) up to this critical size was shown to result in a decoupling, relative to the tamped case, by a factor of up to 120 for a given type of material in which the explosion occurs. (Further, an additional muffling factor of 2.5 can be achieved by detonating the explosion in a harder medium than that used in the Hardtack II Series.) The theoretical prediction of the possibility of sizeable decouplings was confirmed in the Cowboy series of underground chemical explosions.**

These considerations led the Berkner Panel to recommend an intensive program of seismic research and development, in order to increase understanding of seismic phenomena and to develop more sensitive instrumentation that would close the gap between what had originally been expected in the way of seismic surveillance of nuclear explosions, and what now seemed to be the case.*** By September 1959, such a program, designated Project Vela Uniform,**** was established under the direction of the Advanced Research Projects Agency (ARPA)

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* See Ref. [20], part 2, pp. 851-864.

** Preliminary evaluations of the recent Gnome underground atomic shot tend to contradict the conclusions of the last two paragraphs. The 5-kt shot, set off on Dec. 10, 1961 in a large salt cavern near Carlsbad, N. M., was not only detected at stations up to 7200 miles distant, but little, if any, of the expected decoupling appeared. (San Francisco Chronicle, p. 1, Dec. 20, 1961; New York Times, pt. 4, p. 8E, Dec. 24, 1961.)

*** See Ref. [20], part 2, pp. 643-838 for the report of the Berkner panel, which is dated March 21, 1959.

**** Part of a large project, including Vela Hotel and Vela Sierra for the investigation, respectively, of space-based and surface-based detection of high-altitude detonationa.

of the Department of Defense. Implementation of the program was undertaken later by the Air Force Technical Applications Center (AFTAC). Although the program is predominantly concerned with seismic means of detection, non-seismic means are also being studied.

Phenomena Associated with an Underground Nuclear Explosion

When a nuclear device is detonated underground, it may at least theoretically be detected by means of the energy it emits in various forms: seismic, electromagnetic, and the kinetic energy of radioactive particles. Of these, it is unlikely that radioactive particles would be detectable at any appreciable distance from the explosion, nor would electromagnetic energy at extremely high frequencies (light, heat, etc.). (The heat energy released by a bomb might, by conduction, heat the surface of the earth above the site of the explosion, whence the bomb could at least in theory be detected by, say, an infrared-detecting satellite; but, in view of the large number of natural and man-made "hot spots" on the earth's surface, this scheme of detection seems impractical.) The most promising radiations, from the viewpoint of long-range detection, are those in the form of seismic waves, and of electromagnetic waves of frequencies low enough so that they can propagate without exorbitant attenuation either directly through the earth or to the surface and thence by air to the detection site.

Other schemes of detection of the detonation of a bomb, or at least the preparation for it, involve visual surveillance techniques, perhaps by means of satellites. When a nuclear test is conducted, there is often considerable human activity at the test site, which may be observed. Again, if a miscalculation has been made by the testers, the explosion may "blow the top" of the cavity, a detectable event. Further, if a large cavity is being prepared for decoupling purposes by the solution mining* of a salt dome, this operation might be detected by noting an increased salinity of rivers into which the brine is pumped. Such visual surveillance techniques are, however, beyond the scope of this report.

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*A technique in which fresh water is pumped into an underground salt dome, and the dissolved salt is pumped out in the form of brine.

Detection of Low-Frequency Electromagnetic Disturbances*

Two phenomena associated with an underground nuclear explosion appear capable of generating electromagnetic waves at low frequencies. The first is the accelerated motion of the numerous high-speed charged particles propelled from the center of the explosion. The second is the accelerated motion of a highly conducting shell-shaped plasma of ionized air that is driven outward with the shock wave from the explosion; this moving conductor, on cutting through the earth's magnetic field, has induced in it a circulating current proportional to its velocity. **

The frequency spectra of the radiations induced by these sources are of great importance, for the attenuation per unit length suffered by electromagnetic radiation passing through a conducting medium (such as the earth) increases with frequency. One would expect the spectrum of the radiation due to the motion of charged particles to be broad. On the other hand, a distinctive spectrum might be generated by the moving plasma if it were periodically reflected between the walls and the center of the cavity. For this model, O'Rourke and Shuler*** estimate that in a cavity 50 m in radius, with an ionized plasma moving at 5×10^4 m/sec, the current induced in the plasma is equivalent to 1000 amp circulating in a loop 300 ft in diameter, oscillating at 100 cps. The oscillations would, of course, be damped, but it is conjectured that there would be of the order of 100 significant oscillations. ****

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*The author is indebted to R. Ghose of Space-General Corp., and to R. O'Rourke and M. Shuler of Edgerton, Germeshausen and Grier, Inc., for discussing with him their approaches to this problem; and to T. Cantwell and T. Madden of M.I.T. for providing him with much information on the conductivity of the earth.

**A third mechanism, making use of electrostrictive voltages induced in the earth surrounding the cavity by the action of the shock wave, may be worth investigating, but no data seem available concerning the magnitudes involved.

***Private communication, July 12, 1961.

****There is a question here of how many cycles of oscillation would escape as radiation from the cavity before the fireball fused the walls, making them highly conductive.

Now, at a frequency f, the skin depth -- i.e., the distance in which the intensity of the radiation is decreased by a factor of e -- is $1/\sqrt{\pi f \mu \sigma}$ meters, where μ is the permeability of the medium and σ is its conductivity in rationalized mks units. Taking μ to be the permeability of free space ($4\pi \times 10^{-7}$ henrys/meter), and taking a typical value of 10^{-4} mhos/meter for σ [9,25], one finds skin depths of 16 km or 10 mi at 10 cps, 1 mi at 1000 cps, etc. These estimates are based on a typical value of σ at the earth's surface, where the rocks and earth are highly permeated with water. If the conductivity many kilometers beneath the surface were orders of magnitude lower, say 10^{-8} mhos/meter, the estimates would increase by a factor of 100, and long-range detection of radiation travelling directly through the earth would begin to look feasible. Unfortunately, there is no evidence that such a decrease in conductivity occurs; indeed, preliminary measurements* indicate that the conductivity at great depths is close to that at the surface. Thus, it would seem that the major hope for detection of the electromagnetic radiation from an underground bomb is the ability to measure the radiation which travels up to the surface and then via the air to the distant receiving site. Since there will be considerable loss at all but the lowest frequencies in travelling up to the surface, and an additional large loss in traversing the earth-air interface, and since atmospheric noise at low frequencies is liable to be quite high, this hope seems slight.

Some Facts from Seismology

Before discussing various seismic means of detecting bombs and distinguishing them from earthquakes, it will be necessary to summarize, briefly and not at all completely, the several forms seismic waves assume.** Basically, these waves may be divided into two groups: body waves and surface waves. The former penetrate deeply into the earth, and are returned to the surface by reflection from interfaces between strata, by refraction caused by the variation of the mass density of the earth with depth, and by travelling straight through the earth's core to the

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*Private communication from T. Cantwell and T. Madden, August 11, 1961

**These data are taken mainly from Refs. [18] and [24].

neighborhood of the antipodes. Surface waves, on the other hand, are confined to the upper part of the earth's crust, travelling mainly just below the earth's surface, and rarely penetrating more than a few kilometers into the earth.

Each type of wave may be categorized almost indefinitely into more special groupings. The two main categories of body waves, denoted P and S by seismologists, are compressional (longitudinal) and shear (transverse) waves, respectively. Each of these may be subdivided further according as the wave is merely refracted, or is reflected from various discontinuities in the earth's crust, reflected from the earth's core, reflected one or more times from the earth-air interface after being returned to the surface, ducted by channels formed by strata, transmitted through the core, etc. Mode conversions from P to S and S to P also occur at discontinuities in the medium, and must be taken into account in categorizing body waves.

Some possible configurations of body waves are shown in Fig. 1,* together with the symbols by which they are denoted. Figure 1(a) shows various gross configurations for a distant source that is near the surface. Figure 1(b) shows some additional P waves which may be distinguished when the source is deep; e.g., pP, which is characterized by a reflection from the earth-air interface close to the source, prior to deep-body refraction. Other close-reflected waves, not shown, are sS, sP and pS, the latter two exhibiting mode conversion on reflection from the surface. Figure 1(c) shows a detailed picture of paths for several P and S waves travelling in various layers of the earth, for a case in which the source and observatory are separated by a small angular distance. Pn and Sn are the basic body waves observed at large distances, and, as in Fig. 1(a), are often denoted simply by P and S, respectively.

There are also two main categories of surface waves: Love and Rayleigh waves, named after the men who mathematically explained their existence. The first of these is a transverse wave with no vertical component; the second has both vertical and longitudinal components, causing particles in the medium to have a

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* These figures are taken from [18], pp. 72, 89 and 92; a minor change has been made in Fig. 1(c).

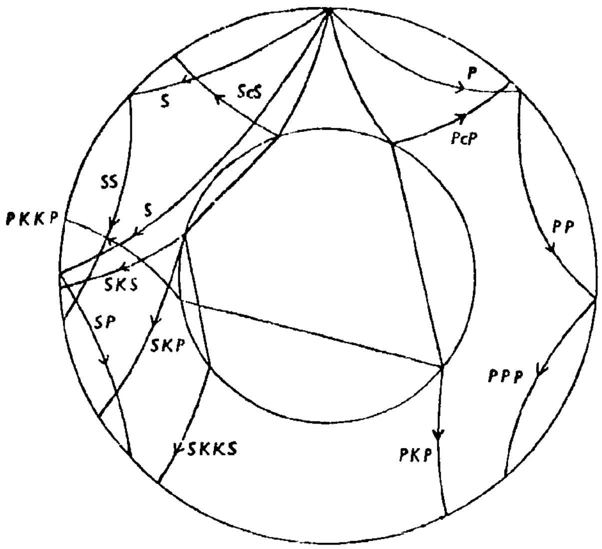
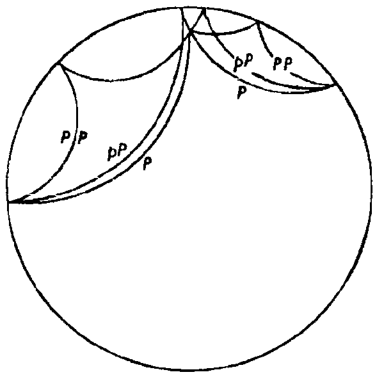


Fig. 1(a). Paths of the principal pulses observed in distant earthquakes.

Fig. 1(b). Rays in a deep earthquake. S follows almost the same paths as P, SS as PP, sS as pP. sP is reflected somewhat nearer the epicenter than pP.



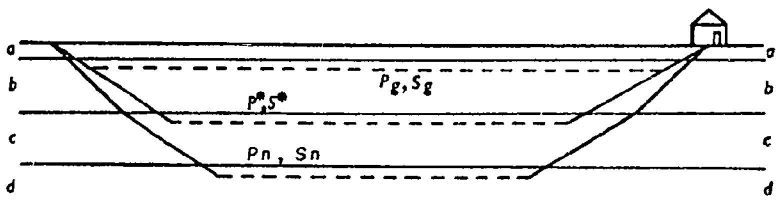


Fig. 1(c). Diagram of the probable paths of the six pulses observed in near earthquakes for a focus in the sedimentary layer. Broken lines indicate waves propagated along or near to boundaries. The horizontal scale is, of course, much smaller than the vertical; the angles are approximately correct. aa, sedimentary layer; bb, upper layer; cc, intermediate layer; dd, lower layer.

"Figures 1(a)-(c) have been taken, with permission, from H. Jeffreys, "The Earth, its Origin, History and Physical Constitution," Fourth edition, Cambridge Univ. Press, 1959. Figure 1(c) adapted from above.

retrograde elliptical motion. The most important forms of Love and Rayleigh waves are denoted LQ and LR, respectively.

The various forms of seismic waves differ in their velocities and their frequency spectra as well as in their paths and modes of propagation. P waves have velocities ranging from 5 to 8 km/sec (depending on the layer through which they travel) and a spectrum of periods ranging, roughly, from 0.1 to 7 sec. S waves travel at 3-5 km/sec and have a period range of 0.25-7 sec. The velocity of propagation of surface waves is a function of period, the longer-period waves penetrating into deeper and denser parts of the earth, and hence travelling faster. The exact curves of velocity vs. period depend on the medium through which the waves travel, differing, for example, for continental and oceanic paths. Representative phase-velocity values are: 4 km/sec and 4.5 km/sec, respectively, for 60-second period LQ and LR waves; 3 km/sec for 10-second period LQ and LR waves [18]. Group velocities are, of course, lower, in some cases by about 1 km/sec [8]. It is to be noted that the dominant periods of surface waves are considerably larger than those for body waves.

Extensive measurements of the velocities of seismic waves have been made over the years by seismologists. For body waves of various types, these measurements are usually condensed into curves of travel time vs. angle of arc subtended between source and receiver (see [18], facing p. 122). For surface waves, velocity is usually plotted as a function of period (see, e.g., [2], [6] and [8]).

No discussion of seismic phenomena could be deemed even approximately complete without a consideration of seismic noise (microseisms). At any seismometer location, this noise originates from both local and distant sources. The local noise, which is usually spatially incoherent, arises from man-made sources (local traffic, etc.) and also from natural sources (wind in trees, streams, etc.). Noise generated at a distance apparently arrives in the form of spatially coherent surface waves, but its sources are not well understood, it has been conjectured that it is somehow connected with storms at sea and with the motion of cold fronts.

Many efforts have been and are being made to measure the spectrum of seismic noise.* Perhaps the most comprehensive survey of these measurements is given in reference [7], from which Fig. 2 is taken. The curves in this figure represent a distillation of data taken from about one hundred papers in the literature. Only data from land-based measurements were available, and data obviously connected with local noise sources and with transients from earthquakes and explosions were excluded. The "max" and "min" curves are to be considered, for any given value of period, as roughly bounding the noise which may be expected during any short interval of time (e.g., one day); the short-time noise powers at different values of period may not vary together, however, so that short-time "spectra"** may differ markedly in shape from any of the three curves shown. Data are almost nonexistent for periods above 50 seconds, but a few points in the upper right of the chart represent the noise due to long-period tidal sources, which cause forced oscillation of the earth as a whole rather than propagating waves.

Little need be said in way of discussion of the curves of Fig. 2, other than to call attention to the very pronounced noise peak in the vicinity of 4-8 seconds, which seems to be associated with ocean waves.

A word concerning seismometers will be of interest at this point. These instruments, which usually contain pendulums and other components which have natural frequencies, cannot respond with equal amplitude to waves over the entire period range spanned by body and surface waves. A well-equipped seismographic station therefore generally has both long-period and short-period instruments, the former responding mainly to surface waves and the latter mainly to body waves.

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* Three current efforts are at M.I.T. (Prof. Simpson), the University of California (San Diego) [17], and Columbia University's Lamont Geophysical Laboratory (Prof. Oliver).

** It is important to note that the ordinate values in Fig. 2 (microns) are incorrect for a spectral <u>density</u>. According to N. A. Haskell of the AFCRC Terrestrial Sciences Laboratory (private communication), a reasonable rule-of-thumb is to interpret the ordinate at any period as the rms noise in a one-octave period range centered on that period.

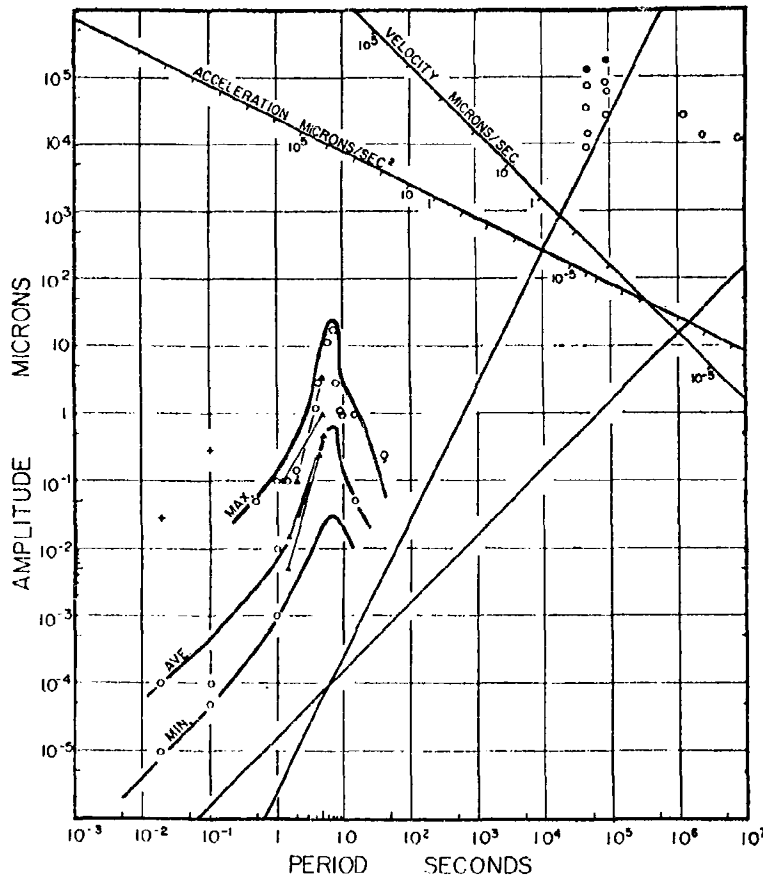

Fig. 2. The seismic noise of the earth's surface.

Reproduced with permission of Bulletin of The Seismological Society of America.

Further, each seismometer will generally be a three-component type, capable of recording separately the vertical, North-South and East-West components of ground displacement (or velocity or acceleration). Since body waves penetrate deeply into the earth, they arrive at the surface with an almost vertical direction of propagation, so P waves will be noted principally on the vertical-component record, while S waves will appear principally on the N-S and E-W records. On the other hand, since surface waves travel "parallel" to the surface, Rayleigh (LR) waves (retrograde elliptical motion) will be recorded by the vertical seismometer and at least one of the horizontal seismometers, while Love (LQ) waves will not show a vertical component.

Means of Seismic Detection and Identification

After this brief introduction to seismology, it is possible to outline various seismic means that have been proposed for detecting and identifying nuclear explosions. A discussion of the relative merits of these techniques is postponed until the next section.*

The principal method proposed by the Geneva Conference of Experts, and the one upon which its estimates of detectability and identifiability of nuclear explosions were based, uses the criterion of direction of first motion of the first-arriving wave. It is well established that, of all the types of waves generated by a seismic source, the first to arrive will be a P wave. This first arrival is usually the deep-body P wave (Pn) which, even though it travels a longer path than a surface wave, has sufficiently high velocity to arrive first. In other cases, when Pn is missing, the first arrival may be a P wave guided through a layer in the earth's crust -- cf. Fig. 1(c). In any case, the important point here is that the first arrival is a short-period longitudinal wave, arriving at the observatory almost vertically, and will thus be recorded on the short-period vertical seismograph.

Now, for an underground explosion, the first motion of the ground in the immediate vicinity of the explosion should be compressional -- i.e., outward from the explosion -- in all directions. It is therefore conjectured that the first

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* Bibliographical references referring to realization of these techniques are also deferred until the next section.

motion observed at all seismographical stations, regardless of location, will be compressional -- i.e., upward on the vertical seismometer. On the other hand, an earthquake arises from slippage at a fault (see Fig. 3), and it would therefore be expected that the first motion transmitted via a P wave would be compressional in some directions and rarefactional in others. For example, if the fault shown in Fig. 3 is oriented vertically, and the slippage is horizontal as shown, one would expect compressional first-motion records at stations in the first and third quadrants relative to the fault, and rarefactional records in the other two quadrants. The identification criterion for this method thus involves a search for an azimuthal variation of direction of first motion of P waves. *

The search for azimuthal asymmetry may also be applied to surface waves. It will be recalled that surface waves are very dispersed in time, because of the variation of their phase velocity with period. However, if the curve of velocity vs. period for the path travelled by the disturbance is known, and the distance travelled is also known, then the phase distortion of the record can be corrected. If this correction is applied, "source functions" -- i.e., the recorded waveform referred back to the source** -- may be derived for stations at several azimuthal bearings from the source. One may then conjecture that because of the azimuthal asymmetry of the forces generated in an earthquake, the source functions derived at different azimuthal angles will be different for an earthquake, while they will be very similar for a bomb.

Other methods of distinguishing earthquakes from bombs may be listed quickly.*** One set of methods depends upon assumed differences between the

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* It may incidentally be noted here that sufficient data are available on times of travel of P waves so that measurements of the time of first arrival, made at several observatories throughout the world, usually serve to define the location of the source to a high degree of accuracy.

** There is usually little amplitude distortion in the medium. In the process of correcting for the medium's phase distortion, the amplitude and phase distortion caused by the recording instrument should also be corrected, however.

*** It is assumed here that the occurrence of a disturbance has already been detected.

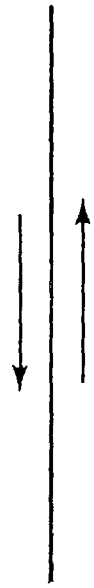

Fig. 3. Motion at a fault.

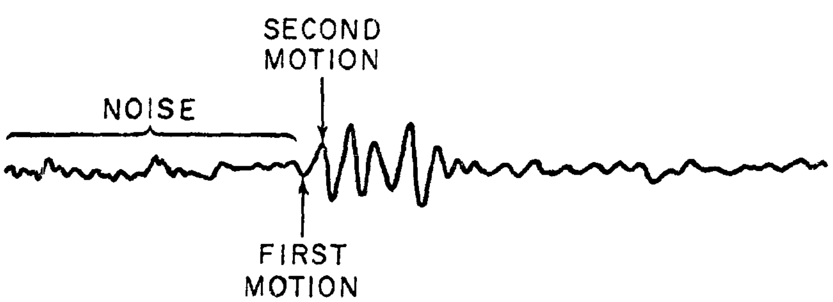

Fig. 4. A representative P wave signal.

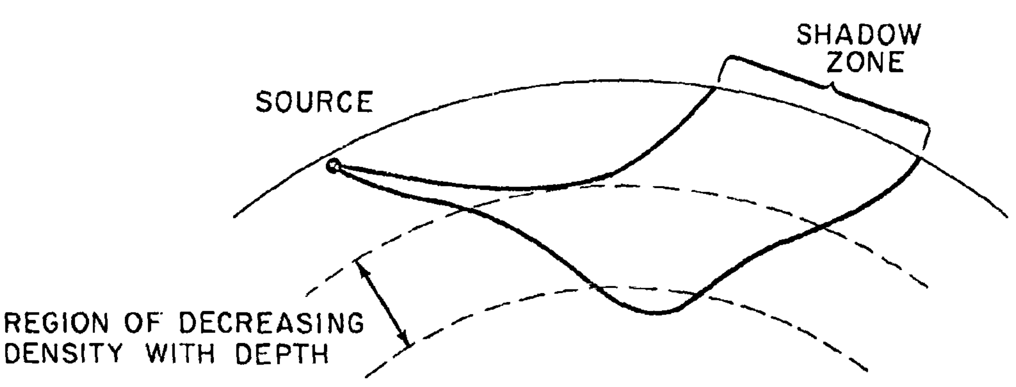

Fig. 5. Two wave paths, illustrating the shadow zone.

mechanisms of bombs and earthquakes, other than the azimuthal differences already described. For example, it may be conjectured that since the explosion of a bomb is essentially a compressional phenomenon, the shear waves generated by a bomb (if any) will be considerably weaker than for an earthquake of equivalent strength; one might therefore use the ratio of energies or amplitudes of compressional and shear waves as a discriminant of the type of source. Again, the ratio of amplitudes of the two (transverse) components of the S wave from an earthquake, and hence the wave's direction of polarization, is intimately associated with the orientation of the fault plane, so one might expect considerable differences in the S-wave polarization pattern from an earthquake and from a bomb. There may also be differences in the relative energies of surface and body waves radiated by bombs and earthquakes, or differences in the energy spectra of either the surface waves or the body waves or both.*

Another category of techniques involves estimating the depth at which a detected occurrence took place, for if the event originated more than a few kilometers below the surface of the earth, it is safe to ascribe it to natural causes. One possibility is to measure the difference in arrival times of the pP and P waves shown in Fig. 1(b), which would be a direct measure of the depth of focus. Other methods might involve measurement of the spectrum of the surface waves, or of the ratio of energies in surface and body waves, both of which would tend to vary with depth of focus.**

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*There is some reason to expect that the long-period surface waves from an earthquake in a given area may be characterized by a lower dominant frequency than those from an explosion of the same magnitude in the same area (see [20], part 2, p. 601). This, and the same type of effect for body waves, is reported to have been very markedly observed in some Russian measurements [22], in which the locations and magnitudes were not controlled.

**The recent Gnome test (see footnote **, page 4) led to another suggestion for an identification technique. We quote from the New York Times, December 24, 1961, part 4, p. 8E: "The tracing which Professor Leet recorded on his seismograph following the Gnome explosion show (sic) two peculiar kinds of ground waves, which, he reported, he has picked up only once before -- during the first test of the atomic bomb at Alamogordo, N. M., in July, 1945. These two waves, he said, have not been found on records of natural earthquakes, and may thus serve to 'finger-print' man-made explosions." Professor Leet is in charge of the Harvard seismological station.

Evaluation of Proposed Techniques

The difficulty in evaluating the techniques outlined in the previous section lies in the fact that pertinent data are sparse for earthquakes, and virtually non-existent for underground explosions. Despite this, some observations may be made.

In regard to the criterion of direction of first motion of P arrivals, a major drawback is that the first motion is apt to be quite small; if it is small enough to be obscured by the noise, the second motion, which is generally larger and is in the opposite direction, may be mistaken for the first motion, thus giving precisely the wrong indication. (See Fig. 4.) The situation is aggravated by the fact that a "shadow zone" exists for deeply penetrating P waves (i.e., Pn waves) from roughly 1000 to 2000 km from the disturbance. This shadowing effect results from the fact that over a certain range of depths below the earth's crust, mass density decreases with depth rather than increases, causing refraction in a downward direction. (See Fig. 5.) Although other types of P waves may be noticed in the shadow zone (e.g., Pg and P^{*} -- cf. Fig. 1(c)), their signal-to-noise ratio is generally too small to permit unambiguous reading of first motion. An illuminating discussion of the problem of determination of direction of first motion appears in a paper by Romney [27], which gives results of measurements on the Hardtack II series of underground nuclear explosions:

> "The seismograms shown ... illustrate the problem of determining the direction of first motion. In principle, the first motion from a blast should always be compressional. It may be seen that the first motion is recorded compressional at some stations and rarefactional at others. There seems to be no systematic dependence upon the distance, with the obvious exception that the first wave is strong and compressional at small distances (less than about 700 km). At distances greater than 1100 km and less than 2650 km, it is not known with certainty whether the first motion was observed at any station on either Logan or Blanca.* At some stations, (for example, the station at 2300 km) there is apparently clear, rarefactional first motion in spite of a signal-to-noise ratio** of at least ten."

It was such results as that quoted above which led the Berkner panel to its

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* The names of two of the blasts in the series. Logan had an approximate yield of 5 kt and Blanca an approximate yield of 19 kt. (Author)

** For the strongest part of the P wave. (Author)

conclusions about the efficiency of the Geneva system.* It is to be noted here that the Hardtack II measurements did not test the hypothesis that the first motion, when readable in the noise background, is indeed independent of azimuth. But even if this is so, the measurements showed that, at least with equipment of the sensitivity used in the tests, the criterion of first motion is not dependable: if a compressional first motion that is independent of azimuth is noted, one might reasonably suspect the source to be a bomb, but the opposite result is not sufficient to eliminate this possibility.

If the first-motion criterion is valid, i.e., discrimination could indeed be effected in the absence of noise, the obvious procedure for utilizing it is to try to increase the signal-to-noise ratio so that the first motion is discernible. Several methods of noise reduction may be used.

1) The effects of locally generated noise (wind noise, etc.) may be reduced by placing the seismometers in deep holes.

2) Spectral filtering may be used to capitalize on differences in the spectra of the P waves and of the noise. (The dominant frequencies of the two spectra are of the order of 1 cps [27], and 0.2 cps (see Fig. 2), respectively; the second figure is for surface-wave noise.)

3) Spatial filtering, i.e. a phased array of seismometers, may be used.** This would have three effects. First, if the seismometer spacing in the array is large enough (thousands of feet) one may expect that the locally generated noise at the different array elements would be incoherent and would add power-wise, while with proper phasing the signal contributions would add voltage-wise. This would yield, theoretically, an improvement in voltage signal-to-local noise ratio of $\sqrt{N}$, where N is the number of array elements. Second, the directional effects of the array may be counted on to discriminate against surface-wave noise originating at a distance, since constant-phase surfaces of such noise will move more or less horizontally, while constant-phase surfaces of P waves will arrive with almost vertical motion. Finally, since the elements of the array would be phased for

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* See page 3 of the present report.

** See reference [21], pp. 37-45.

P-wave velocity, an additional discrimination against surface-wave noise, which travels at a much lower velocity, would be achieved. * The last two effects would tend to increase the signal to surface-wave-noise ratio as $\sqrt{N}$, if the element spacing is large enough to ensure spatial incoherence of the surface-wave noise at different elements.

The analysis and design of large seismometer arrays are being pursued under Project Vela Uniform. ** Several drawbacks to their use may be noted. First, because of local anomalies in propagation velocity, one would not expect to be able properly to phase elements that are too greatly separated in distance. For this and other reasons, the over-all size of the array must be limited. On the other hand, in order to ensure incoherency of the noises at all elements, adjacent elements should not be spaced too closely together. The number of elements in the array, and therefore the improvement afforded in signal-to-noise ratio, will thus be limited. (Apparently an array size of the order of $N = 30$ is as large as is practical. ***) Secondly, because of the directional effects of the array, provision must be made to scan the array through the solid angle which includes all probable directions of arrival. This can be done by computer, after the seismometer outputs have been digitalized, but for large numbers of elements, the number of computations that must be performed per unit time becomes very large. Thirdly, the installation of each element of the array is quite expensive, as is the requisite computer, and if a network of large arrays is contemplated, the over-all cost may be prohibitive. **** Finally, and most importantly, it may be questioned whether even a very large array will achieve the increase in signal-to-noise ratio necessary to discern first motion at reasonable distances (especially if decoupling factors of the order of 300 are achievable), even postulating the validity of the first-motion criterion.

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* See, e.g., ref. [8a].

** See page 4.

*** Ref. [21], p. 38.

**** See refs. [20], part 1, pp. 318-335 and [21], p. 45.

In regard to the use of surface-wave records to discover azimuthal asymmetries, some interesting results appear in the literature. Aki [1,2,3,4] and Brune [6] have applied the phase-compensation method to the study of earthquakes, the former using records having periods of the order of tens of seconds, the latter using records with periods of the order of hundreds of seconds. They both found marked quadripole (quadrant) patterns of the derived source functions, which were in agreement both with patterns theoretically expected of earthquakes in general and, in particular, with fault-plane data found from other, independent records of the earthquakes studied. Unfortunately, no similar studies have been made for bomb-type sources to check the supposition that the source-function pattern will be isotropic for such sources.

The Aki and Brune studies were only possible because the location of each source studied was known in advance. From this knowledge, the paths from the source to the various recording stations were determined, and, using empirical phase-velocity vs. period curves for these paths,* the phase shift suffered by each frequency component in travelling over each path could be calculated. The point to be made here is that the phase-compensation method is one that may be useful in identifying an unknown disturbance, but only after it has been detected and located. Since location is apparently difficult from analysis of surface-wave data, the surface-wave phase-compensation method of identification would therefore have to be used in conjunction with location by body-wave data.**

(It may be noted parenthetically here that a technique similar to Aki's and Brune's is one suggested by Tukey.*** In Tukey's method, the record to be analyzed

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* These curves are determined by comparing the phase spectra, at several stations along a path, of a given disturbance travelling over that path.

** See footnote * page 14. In regard to location with surface-wave data, it is not clear to the present author why measurements of direction of arrival of surface waves, made at several stations, could not be used with a triangulation technique to determine the location of a source; but to his (very incomplete) knowledge, such a method is not used.

*** See ref. [20], pp. 704-756.

is cross-correlated with a "typical" surface-wave record of a disturbance that has travelled over the same or a very similar path. This procedure will compensate the phase spectrum of the signal component of the record being processed, under the explicit assumptions that the "typical" record is essentially noiseless and that the source function that gave rise to the "typical" record is identical to the source function being derived. The first of these assumptions is probably realistic, but the second -- which Tukey justifies by stating that all source functions are essentially impulse-like -- seems invalid in the light of Aki's subsequent work.)

As for the other methods mentioned in the previous section for distinguishing earthquakes from bombs, the data needed for their evaluation are even less complete. Concerning the class of methods that seek to capitalize on differences in the mechanisms of earthquakes and bombs, we may make the following comments.

The use of the ratio of the energies or amplitudes of compressional and shear waves as a discriminant may not be feasible. Romney [27] observed, in the Hardtack II experiments, certain short-period (1-1.5 seconds) shear waves, which might have been either S waves of high-mode surface waves (LG waves). The amplitude of these shear waves was roughly three times that of the vertical amplitude of the P waves. On the other hand, according to D. Linehan,* ratios of the amplitude of S waves to that of P waves for earthquakes are also typically 3:1, or slightly more. If the shear waves observed by Romney are indeed S waves, these two data seem to rule out the amplitude ratio of S to P as a discriminant.

To the author's knowledge, essentially nothing can be said about the use of S-wave polarization patterns for identification of the source; no measurements of these were made in the Hardtack II experiments. Further, although both LR and LQ (surface) waves were noted** in these experiments, their amplitudes were not measured, so no data are available for comparing the relative energies of surface waves and body waves for earthquakes and bombs.

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* Private communication, August 7, 1961.

** Only LR waves had been expected.

Some psycho-acoustic experiments have been conducted by Bell Telephone Laboratories [28], which may be explained as attempts to distinguish between the spectra of bombs and earthquakes by auditory means. Briefly, the method consists of comparing bomb records from the Hardtack II series with earthquake records taken from similar seismometers, by speeding up the records so that their spectra lie in the audio range. The records were first digitalized for computational purposes; then the means of the records were set to zero, the peak value of each record was normalized, and the pre-event noise duration for all records were made equal. The records were then converted to analog audio tape with a time-compression factor of 300. Pairs of sped-up records, each containing one bomb record and one earthquake record in unspecified order, were then transcribed sequentially onto a tape. Observers were asked to listen to the sequences of pairs, and to call out "bomb-quake" or "quake-bomb" after each pair to indicate his estimate of the unknown order. After some training, the listeners were able on the average to identify 96% of the pairs correctly.

It was found that the discriminability was best when the records were limited by filtering to the base-band range of 2-5 cps (0.2-0.5 sec period range). The distinguishing feature of the sped-up records seems to be that a bomb has a more "metallic" sound, indicating stronger high-frequency components than for earthquakes. However, as the BTL people themselves point out, these stronger high frequencies may have been due to the fact that the bomb records were digitalized by hand -- which tends to introduce high-frequency errors -- while all earthquake records were digitalized by machine. Further, the epicentral distances to the earthquakes were generally much greater than the distances for bombs, which may have caused slightly more high-frequency filtering in the transmission medium for the former sources. Final evaluation of the effectiveness of this system of discrimination awaits more carefully controlled experiments.

In regard to spectrum discrimination, a Russian paper [22] indicates that the "period" of a bomb record will be considerably smaller than that for an earthquake record, especially if surface-wave records are compared. Further, the "period" is reported to be an increasing function of epicentral distance for an

earthquake record and essentially constant for a bomb record. The data used to come to these conclusions were taken from two chemical bombs of 1 kt and 3.1 kt and several earthquakes, recorded on various types of instruments. In the case of body waves, "period" means "predominant period", and in the case of surface waves it means " maximum period"; no indication is given of how these "periods" were obtained from the records.

In the category of techniques that involve the determination of the depth of focus, an interesting method that attempts to measure the difference in arrival times of P and pP (see Fig. 1(b)) has been studied at Bell Telephone Laboratories.* If it is assumed that the two waves travel over essentially the same path, and that they both arise from the same source function, then the seismogram will contain some signal $s(t)$, due to the P wave, followed by $-k\, s(t - t_o)$, due to the pP wave. (The negative sign arises from a sign reversal upon reflection from the earth-air interface; k is a reflection ratio, less than unity.) The delay t_o will be a measure of the depth of the event, and it is this delay one wishes to estimate.

The technique used by Bogert is first to try to compensate the spectrum of the seismogram over a given frequency band for the effects of the source function, the attenuation of the transmission path and the frequency characteristics of the seismograph. If this is successful, the $s(t) - ks(t - t_o)$ component is converted, at least as far as the frequency band of interest is concerned, into $\delta(t) - k\delta(t - t)$. The equivalent component of the compensated Fourier spectrum of the seismogram then has a magnitude with "scallops" of peak-to-peak height $2k$ and period $1/t_o$. These scallops are hidden in the spectrum of the noise, so the next step taken is to smooth the magnitude of the compensated Fourier spectrum. (This assumes that the component in the spectrum due to the noise has many fluctuations in a frequency interval of width $1/t_o$.) Finally, the inverse Fourier transform of the smoothed magnitude spectrum is taken. If the processing has been successful, the inverse transform should exhibit a pronounced peak at the origin, and two smaller peaks -- of height $k/(1+k)$ -- t_o seconds on each side of the origin.

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* B. Bogert, private communication, July 6, 1961.

There are many "ifs" in this scheme: if the source functions for P and pP are the same; if the two waves travel very similar paths;* if enough information about the source function, the transmission paths and the seismograph transfer function is available; if the noise component of the compensated spectrum has rapid enough fluctuations; if k is large enough so that the side peaks of the final record can be discerned. The preliminary results of computation seen by the present author were unpromising: in most cases, many spurious noise peaks were present in the final record, and the "true" peaks could only be "detected" through prior knowledge (from other depth-of-focus information) of t_o. At any rate, this scheme would only serve to rule out deep earthquakes, but would be of no use in distinguishing between shallow earthquakes and bombs.

A Suggestion

As will readily be appreciated by the alert reader, the present status of bomb detection and identification techniques is an unenviable one. None of the techniques so far tested seems to be satisfactory for the levels of explosions that must be considered, and none of the proposed techniques seems very promising. **

One may list several attributes of a desirable surveillance system:

1) The operations of detection, location and identification should be achievable from the same basic data, so as to minimize the number of seismometers required. Further, in order to have sensitivity, the raw data that are used should have the highest possible signal-to-noise ratio.

2) The system should not depend too heavily on theoretical assumptions concerning the nature of source functions, transmission paths, etc., since such assumptions, in the present state of knowledge, are usually highly arguable. Neither should it depend on sets of "typical" records, since present knowledge to a large extent precludes definition of "typical".

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* According to R. Phinney of the C.I.T. Seismological Laboratory, the impedance mismatch at the air-earth interface considerably changes the spectrum of the pP wave. (Private communication, August 21, 1961.)

** An exception to this statement is, perhaps, the auditory recognition scheme of Bell Telephone Laboratories [28]; but more and better-controlled tests of this scheme are necessary.

3) The system should be as simple as possible. Such mechanisms as large arrays and numbers of large-scale computers should be avoided if possible.

The requirement of high sensitivity listed in item (1) leads one to consider the use of long-period surface-waves (periods greater than, say, 20 sec). This follows from two reasons. First, the amplitudes of long-period surface-wave records are generally orders of magnitude larger than those for body-wave records; this is due, at least in part, to the fact that surface waves spread out in only two dimensions, and body waves in three, so the latter diminish more rapidly with distance. Second, if the curves of Fig. 2 may properly be extrapolated say another decade to the right, indications are that the noise power per octave in the long-period surface-wave period range will generally be less than in the body-wave range.

If the signal-to-noise ratios obtainable by use of long-period surface waves is indeed several orders of magnitude greater than that obtainable through the use of body waves, the possibility is offered of overcoming the difficulties presented by decoupling factors of 300. The problem is to design a procedure that will use long-period surface-wave records to detect, locate and identify seismic disturbances.

Now, while the phase-compensation method of Aki and Brune appears promising for use by seismologists in studying earthquakes for which other data are already available, we have seen that it is not valuable for location and identification of previously unlocated events, and therefore does not satisfy condition (1). Neither does it satisfy condition (2), for it requires detailed knowledge of phase-velocity curves.

On the other hand, another result of Brune [6] gives hope that mere measurement of (phase-uncompensated) surface-wave amplitude may suffice for bomb-earthquake discrimination. For the earthquake Brune studied, the azimuthal Rayleigh-wave amplitude pattern showed the same distinct quadrant (quadripole) behavior as the source-function pattern derived from phase compensation. Note that such a radiation pattern measurement would not

require prior knowledge of the source location, as does the measurement of the source-function pattern.

These and other considerations connected with the requirements listed above lead to the following suggestion.

Imagine a geographical network of single, vertical-component, long-period seismometers, for the measurement of the vertical component of Rayleigh waves. At each seismometer, a single measurement is made: a short-time energy measurement, of length T, of the energy in some given band of periods. The energy measurements are all transmitted to a central control post.

Now imagine that a seismic event occurs at point X. Surface waves are sent out in all directions, presumably in a quadripole or other anisotropic pattern if the source is an earthquake, and in an essentially isotropic pattern if the source is a bomb. The energy radiated in the band of periods being measured travels outward with some group velocity V_g. (We assume that a narrow enough band is taken so that V_g is almost constant across the band.) Suppose that the frequency group considered has a duration T_g. Then at time t after the event, all stations in the seismometer network within the annulus from distances $V_g(t - T_g - T)$ to $V_g t$ from X will show increases in energy above the background-noise energy; stations in the annulus' "center" will have reached their maximum energy. If the energies were displayed at the control post on some mapping device such as a PPI scope, a "ripple" would be seen progressing outward from X, with more or less constant brightness as a function of azimuth for a bomb and with a quadripole pattern of brightness for an earthquake. Hopefully, analysis of the ripple as it progresses would yield enough information to locate the source and its time of occurrence, at least accurately enough so that a thorough analysis of detailed body-wave records taken at standard observatories throughout the world will pinpoint the event. (Such body-wave records might have had small enough amplitudes to have been overlooked without some a priori information about where to examine the records.)

A few numbers will illustrate the system. It seems reasonable to take the energy integration time T to be equal to T_g. Now suppose that the band of periods 40-60 seconds is taken. If the source function is of short duration (say

10 seconds or less), we may expect a group length roughly equal to the reciprocal of the bandwidth; i.e., $T_g \cong 120$ sec. If we take the group velocity to be, say, $V_g \cong 4$ km/sec, then at any given time all stations within an annulus roughly 1000 km (600 mi) wide will simultaneously show increases of energy of various amounts. In order to have sufficient numbers of readings to establish ripple and radiation patterns, perhaps the stations should be spaced by half this width, i.e., 300 mi One may guess that a close computer study of the times at which the several stations go through their energy maxima as the ripple progresses outward would serve to locate the source within, say, 50 km (30 mi), depending on the signal-to-noise ratio. A similar guess concerning the accuracy of an estimate of time of occurrence might be, say, ± 10 sec, subject to uncertainties in knowledge of V_g.*

A rough calculation may also be made of the signal-to-noise ratio that might be expected. Suppose that the source is a 1 kt explosion. An empirical relationship** given by Romney [27] puts this at around 3.6 on the earthquake magnitude scale. Another empirical relationship, given by Gutenberg [14], predicts that for this magnitude the <u>horizontal</u> component of a surface-wave group in the region of a 20-second period will have a displacement amplitude, at a distance of 1000 mi from the explosion, of roughly 1/3 micron. We take this to be of the right order of magnitude for a <u>vertical</u> displacement in our band. Now, Fig. 2 indicates a maximum rms noise amplitude of roughly 1/30 micron in our band.*** Thus, the peak signal-to-rms noise ratio for a 1 kt explosion at 1000 mi should be about 10; a similar calculation gives a signal-to-noise ratio of about 3 at 2000 miles.**** It would therefore seem that, even with maximum noise, the ripple

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*Note that V_g could be ascertained by measuring the speed at which the ripple progresses.

**Derived from body-wave data. We assume this is applicable to surface waves also.

***See footnote **, page 11. Note that this does not take local noise into account.

****This checks with our expectation that surface waves obey an inverse-square law, as opposed to an inverse-cube law for body waves.

would be easily detectable and identifiable out to 2000 mi for the equivalent of a 1 kt tamped explosion.

To be sure, the picture given above has been somewhat oversimplified and idealized. First, the group velocity will not be constant over the frequency band observed; this will cause T_g, and hence the size of the annulus of energy, to increase as the ripple progresses. Second, V_g will no doubt vary with azimuth and distance, depending on the geological structure of the part of the earth's crust being traversed by the wave; this will cause the annulus to deform into other shapes as the ripple progresses. However, neither of these effects changes the essential features of the scheme, but merely enlarges the class of ripple patterns to be considered at the control post.* Third, we have not considered the effects on the system of several bombs or earthquakes occurring at roughly the same epoch, nor the effects of ripples going around the earth one or more times.

Among the advantages of the scheme, one may list the following:

1) The individual stations are extremely simple, and should require no attendants and little maintainence. Although there will probably need to be more of them than were proposed in the Geneva system, their relative simplicity and economy should compensate for this, political considerations aside. Because of the simplicity of the individual station, one may consider extending the network to oceanic areas by imbedding seismometers in the ocean floor. This would greatly increase the effectiveness of the system, especially since ocean-bottom seismometers are essentially noiseless compared to those on land [12].

2) The data link from station to control post is virtually nonexistent: what is required is the transmission of an energy measurement every 10 seconds or so. Since the bandwidth and power requirement for such a data link are extremely small, solar-battery operated radio transmitters (mounted on buoys for the oceanic stations) would probably suffice. Unsuspicious jamming of these links would be difficult.

*One possible scheme for pattern recognition is to take photographs of the display every 10 seconds or so, and then speed them up to a motion-picture sequence.

3) The system makes use of the detailed structure of a radially symmetric, moving energy pattern. It is almost impossible that the locally generated, spatially random noises at the various stations would reproduce such a pattern, and very unlikely that a spatially coherent surface-wave noise would do so. (If the latter did, it would probably have arisen from an earthquake, and would be identified as such.)

4) Because of the large wavelengths involved, it would be very difficult to deform a bomb's radiation pattern by firing a phased succession of explosions in a pattern (e.g., along four straight lines from a common point, to form a quadripole pattern). The possibility of shaping a cavity to give close-coupling in some directions and decoupling in others would have to be investigated, however.

All that the author can add at this point is that the above scheme seems to be worth further consideration.

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* This is by no means complete, balanced, or necessarily even representative, but merely indicates the literature the author had time to study or scan during the present investigation. For a more complete bibliography, see reference [20], part 1, pp. 456-469.

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